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SMOOTHED PARTICLES HYDRODYNAMICS SIMULATION OF A U-TANK IN FORCED MOTION

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Abstract. The hydrodynamic forces generated by the water moving inside a U-shaped tank are predicted by using the open-source Smoothed Particle Hydrodynamic (SPH) solver *DualSPHysics*. In particular the study focuses on the roll moment prediction of the U-tank undergoing forced roll motion at different frequencies. The sensitivity of the hydrodynamic prediction with respect to variations of particle resolution density is investigated by a systematic set of numerical simulations. Results of the SPH simulations are validated by comparison against available experimental data on a particular U-tank shape and discussed both in terms of roll moment amplitude and phase lag with respect to the imposed motion.

1 Introduction

Anti-Roll Tanks (ARTs) represent a reliable device to reduce ship rolling motion in waves. Even tough they have some known problems in specific operating conditions, e.g. at low frequencies, there is a renewed interest in the form of Liquid Tuned Damper (LTD) devices for applications other than ships such in Wave Energy Converters (WECs) [1] and both onshore and offshore wind turbines [2, 3]. In the recent years CFD have started to be used in Simulation Based Design (SBD) frameworks to reach reliable predictions of the hydrodynamic behaviors of such a devices [4, 5, 6]. Considering ARTs from a hydrodynamic perspective there are some relevant non-linear phenomena that can fall in the categories of the *sloshing* and, eventually, of *slamming* which should be properly addressed by using high fidelity CFD solutions. There are many studies dealing with CFD analyses of partially filled rectangular tanks carried out by using different techniques. Smoothed Particle Hydrodynamics (SPH) technique has been applied to this class of problems [7, 8, 9],

reaching good agreement compared to experimental data, both in terms of dynamics and global loads.
In the present research an open-source SPH solver called *DualSPHysics* [10] has been used to analyze the forces and the moments exerted by a U-tank undergoing forced oscillation at a fixed motion amplitude. Results of the CFD simulations are validated by comparison against available experimental data on a particular U-tank design [11]. Results are discussed in the light of the assumptions of the selected CFD method, both as roll moment amplitude and phase lag with respect to the weave.
This SPH solver has been widely used in many coastal engineering studies (see for instance [12, 13, 14, 15, 16]) and, in a less extent, for naval architecture related problems (see e.g. [17, 18, 19, 20]). Such a SPH method, relying on a Lagrangian representation of the fluid flow, is particularly suitable for free surface flows with fragmented sprays such as the one experienced in sloshing in partially filled tanks.

2 Backgrounds of Anti-Roll Tank Physics and Design

The shape of a passive ART mainly depends on the hull type on which it will be installed. Despite possible local changes, two most used geometries show a rectangular or a U-shaped cross section. The latter shape has been considered in the present study. Compared to a rectangular tank the free surface of a U-shaped tank is generally divided in two parts, except for very shallow water depths. Particularly at relatively high water depths this will reduce the possible water impacts on the tank sides due to roll-induced sloshing. This in turn will reduce the dynamics effects involved in the physics of this ART type with respect to classic rectangular ones. Due to ship motions (in particular due to the roll motion) the water inside the ART will start sloshing back and forth exerting a roll moment on the tank and then on the ship itself. Hence the ART design is driven by the need to use such a roll moment as damping correction to ship roll motion. Ideally 90° phase lag with respect to roll motion should be the best situation, meaning that the water motion inside the tank is in phase with roll velocity. Stigter [21] proposed a mathematical formulation to design U-tank and LLoyd [22] provided some further suggestions based on Stigter's method e.g. on the maximum tank angle, on the loss of metacentric height and on the maximum stabilizing moment. Recent studies are instead based on numerical simulations both by RANSE [23, 24, 25] and, in a less extent, by SPH [26] methods.

3 Computational Fluid Dynamics by Smoothed Particle Hydrodynamics

The core of the open-source SPH solver [10] follows the original formulation proposed by Monaghan [27]. This solver has been developed to exploit GP-GPU computation, hence allowing the use of a relatively large number of particles. According to the SPH formulation the flow is solved in a mesh-free Lagrangian framework based on particles description. Field variables (e.g. V, ρ or p) and their derivatives are represented in a continuous integral form by a suitable kernel function (*kernel approximation*) and then discretized over the computational domain (*particle approximation*). Field variables on a specific particle are then computed by approximation using the nearest neighbor particles.

Giving a function $f(x)$ its integral form is expressed according to Eq. (1):

$$f(x) = \int_{\Omega} f(x')\delta(x - x')dx' \tag{1}$$

Using a kernel function $W(x - x', h)$ depending on a smoothing length h, Eq. (1) can be written in terms of Kernel approximation as in Eq. (2). Such a kernel is substituted by proper analytic functions that vanish for separations greater than kh (being k a given constant). The cubic spline kernel function has been chosen.

$$\langle f(x) \rangle = \int_{\Omega} f(x')W(x - x', h)dx' \tag{2}$$

Pressure are computed by the state equation of Eq. (3) assuming water as a weakly compressible fluid. c_0 is the sound speed ranging from 50 m/s up to 250 m/s to ensure $Mach < 0.1$ and γ is a constant generally taken equal to 7.

$$p = \frac{c_0^2 \rho_0}{\gamma} \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] \tag{3}$$

Both the mass and the momentum conservation laws, Eq. (4) and Eq. (5), respectively, are written in terms of particles approximation as follows:

$$\frac{d\rho_i}{dt} = \sum_{ij} m_j \left(u_i - u_j \right) \nabla_i W_{ij} \tag{4}$$

$$\frac{d\mathbf{u}_i}{dt} = -\sum_{ij} m_j \left(\frac{P_i}{\rho_i^2} - \frac{P_j}{\rho_j^2} + \Pi_{ij} \right) \nabla_i W_{ij} + g \tag{5}$$

The summation over the two indexes i and j accounts for particles interactions; m, u and P are the particle mass, velocity and the pressure at a particle respectively. Π_{ij} is a force contribution used to avoid tensile instabilities. being the artificial viscosity coefficient α the main parameter that controls this additional force term. A further diffusive term is introduced in the continuity equation by the *delta-SPH* formulation (see for instance [28]) in order to reduce density fluctuations generated by the combination of the stiff density field described by the state equation and the natural disordering of the particles, resulting in high-frequency low amplitude oscillations in the density scalar field.

4 Selected test case and numerical simulation settings

The proposed fluid dynamic study has been performed on one of the U-tanks tested by Field and Martin [11]. They carried out a systematic experimental campaign by varying both the dimensional ratios of the tank and the water depth inside of it. Fig. 1 displays a scheme of the U-tank where the reference system used for the computations has been highlighted. Table 1 instead reports the main dimensions of the configurations used for the numerical simulation.

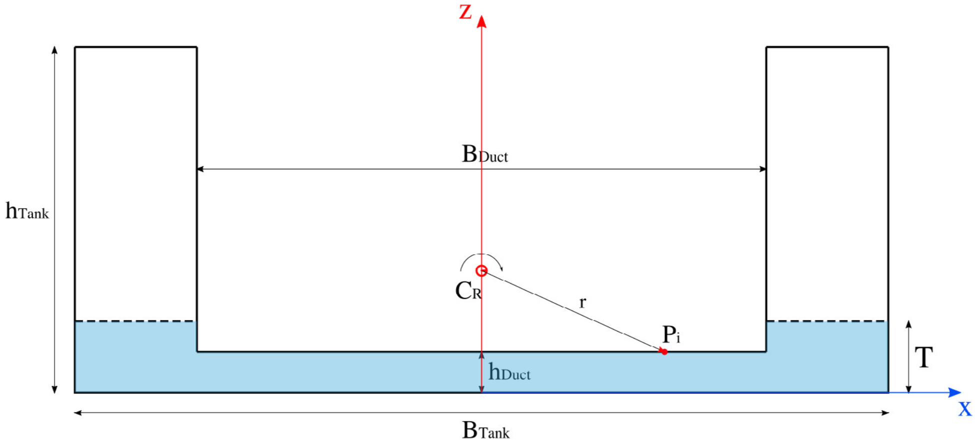


Figure 1: Sketch of the U-Tank. Main dimensions [h_{Tank}, B_{Tank}, h_{Duct}, B_{Duct}], draft T, center of rotation C_R and the position r of the i^{th} pressure probe P_i are indicated.

Table 1: Main dimensions of the U-Tank (full scale).

h_{Tank}	10.0	[ft]	B_{Duct}	24.0	[ft]
B_{Tank}	42.0	[ft]	T	3.0	[ft]
h_{Duct}	1.0	[ft]	Z_{C_R}	4.5	[ft]

The CFD analysis has been performed by scaling the dimensions of the tested U-tank by a factor $\lambda = 8.0$. Froude similarity has been used since it is considered of general validity for sloshing-type problems [29] and for scaling gravity forces. Each of the six SPH simulations has been carried out for 8 roll periods T_{Roll}, hence changing the physical simulated time T_{Max} according to the specific frequency of oscillation ω. According to the experimental tests, the maximum roll angle has been taken equal to $\theta_{44} = 2°$.
Time-varying lateral and vertical forces, $F_X(t)$ and $F_Z(t)$, respectively, have been computed from pressures. The latter have been directly measured by pressure probes uniformly distributed along each side of the tank, placed at a distance along the normal to each boundary equal to $\delta_{Probe} = 1.5h$, being h the smoothing length of the simulation. The time-varying roll moment $M_{44}(t)$ with respect to the center of rotation of the tank C_R has then been computed from the forces. Fourier Transform has been used to obtain the amplitude $M_{44}(\omega)$ and phase $\phi_{44}(\omega)$ of the roll moment. An example of time histories of the lateral and vertical forces on the tank and of the roll moment exerted by the fluid is shown in Fig. 2.

5 Particle density sensitivity analysis

A preliminary analysis of the effect of the particle density with respect to the predicted roll moment has been carried out by using the extrapolation method proposed by Celick [30]. Table 2 reports the results of such a convergence analysis. The extrapolated value of the roll moment obtained by using the two finer densities $Phi_{21-EXTR}$ is very close to the value computed by using the medium size particle density ($\approx 200k$ particles). This

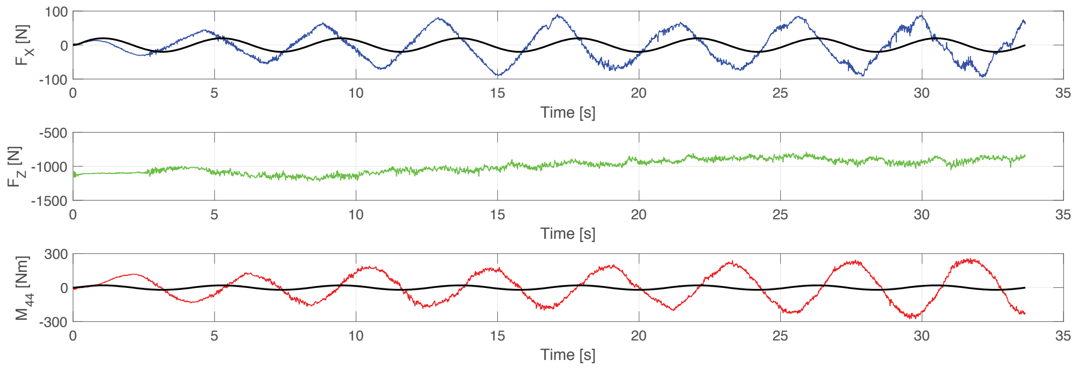


Figure 2: Time histories of the transverse force F_X (top figure), vertical force F_Z (middle figure) and roll motion (bottom figure). Tank sinusoidal motion is shown by a black solid curve.

Table 2: Particle density convergence analysis.

Case	n_P	M_{44}	$\Phi_{21,EXTR}$	$\Phi_{32,EXTR}$	$\Delta\epsilon_{\Phi_{21,EXTR}-M2}$
M1	400k	54.56			
M2	200k	55.40	54.439	56.361	1.76%
M3	100k	48.72			

ensures that the intermediate particle resolution used to compute M_{44} is accurate enough.

6 Validation by comparison against experimental measurements

The SPH simulations have been carried out on a two-dimensional case scaled according to Froude similarity with $\lambda = 8.0$. Hence the numerical results have been scaled considering the width of the tank in order to allow the comparison against the experimental measurements, shown in Fig. 3. A satisfactory agreement between the two results is found, being the trends of both the amplitude and the phase correctly predicted. The maximum deviation on the roll moment amplitude of the numerical prediction with respect to experimental measurements is about $\Delta M_{44} \simeq 12\%$ at $\omega = 0.62$. The prediction is even better close to the peaks where the error is significantly decreased, $\Delta M_{44} \leq 4.5\%$. A greater maximum deviation is found on the phase lag of the roll moment with respect to the imposed (sinusoidal) motion Φ_{44} in the extent of about $\Delta\Phi_{44} \simeq 20\%$. Again at the peak frequencies the quality of the prediction is higher on the phase lag too, being $\Delta\Phi_{44} \leq 5\%$.

Fig. 4 displays the fluid velocity magnitude at four characteristics phases over a roll period, $\psi = [0°, 45°, 90°, 135°, 180°]$, respectively, for two frequencies of oscillation, $\omega = 0.44$ $[rad/sec]$ and $\omega = 0.62$ $[rad/sec]$. The first correspond to the peak frequency while the latter is the one showing the larger error on the roll moment amplitude. Both set of snapshots have been taken at the 8^{th} roll period of the corresponding simulation. At the lower frequency (the peak one) the fluid reaches higher velocities. This is mainly due to gravitational effects during the water transfer from one side to the other. In fact, the slower dynamics of the tank allow the flow to be more affected by the gravity forces. As a

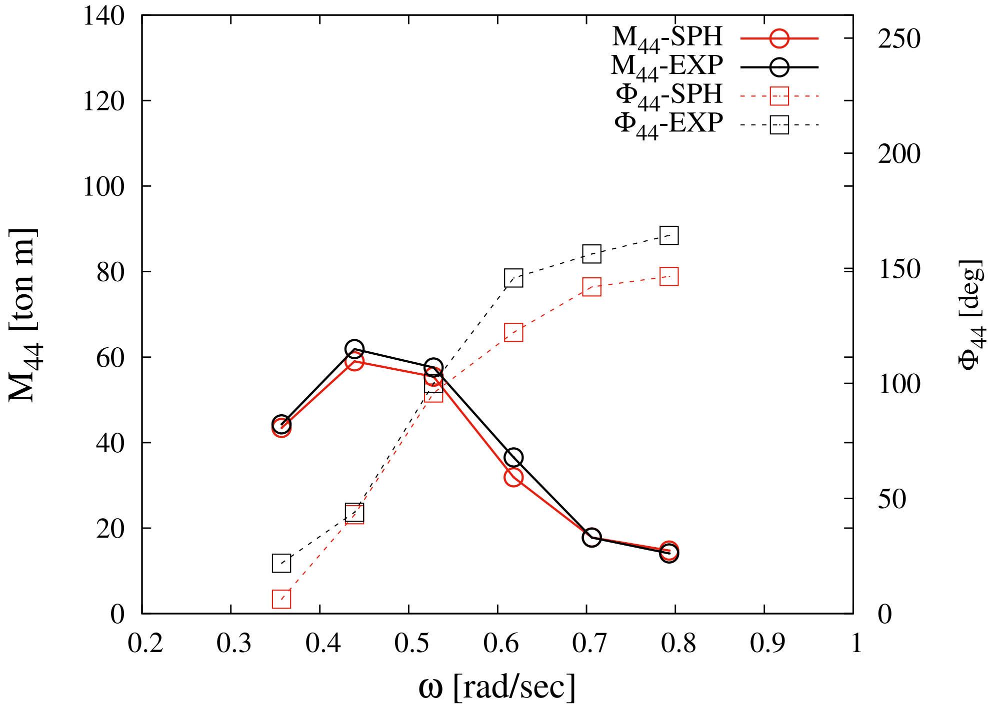


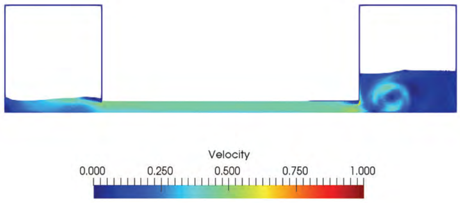
Figure 3: Comparison of the experimental measurements (black) against SPH results (red) in terms of amplitude (circles) and phase lag (squares) of the roll moment.

result the fluid is accelerated for a longer time lapse. For the same reasons, there is also a greater difference between the water levels on the two sides of the tank. Furthermore there are stronger vortexes at the inner corners of the tank that rise due to water re-circulation while the side is filling with water.

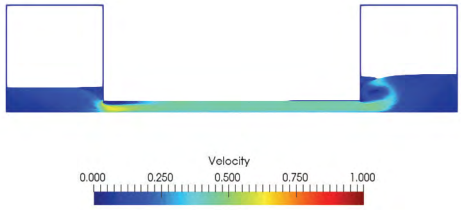
7 Conclusions

A CFD study on a U-Tank under forced oscillating motion has been carried out by using a Smoothed Particle Hydrodynamics (SPH) open source solver. Backgrounds of both the U-Tank analysis and the numerical solver have been briefly presented. The roll moment has been computed by the forces that in turn have been derived directly from pressures over the tank boundaries.

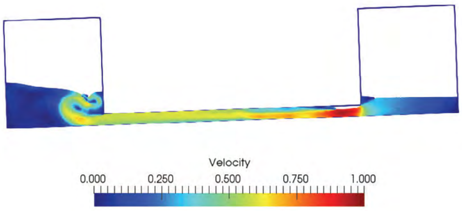
A preliminary analysis of the effect of the particle density on the solution has been carried out. Results have been extrapolated by using the Richardson's method providing information on the convergence properties of the solution. The proposed SPH solution has finally been validated by comparison against available experimental measurements on a U-tank. The tank has been scaled by considering Froude similarity. Both predictions of the amplitude and the phase lag of the roll moment provide satisfactory results. The maximum relative difference with respect to the experiments close to the peak frequencies is lower than 4.5% for the amplitude and 5.0% for the phase lag. It rises up to 12% and 20% at a higher frequency for the amplitude and the phase lag, respectively. Some insights of the fluid flow have also been provided by comparison of the snapshots over



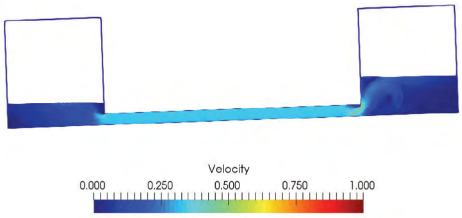
(a) $\omega = 0.44\ rad/sec\ \psi = 0°$



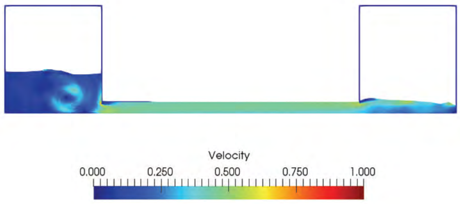
(b) $\omega = 0.62\ rad/sec\ \psi = 0°$



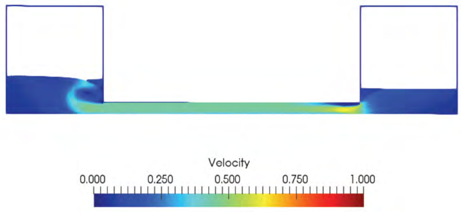
(c) $\omega = 0.44\ rad/sec\ \psi = 45°$



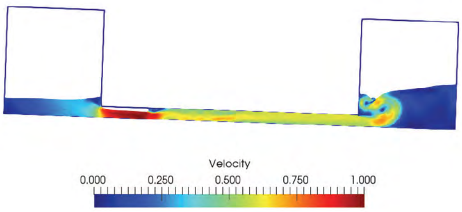
(d) $\omega = 0.62\ rad/sec\ \psi = 45°$



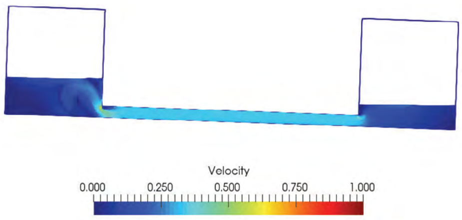
(e) $\omega = 0.44\ rad/sec\ \psi = 90°$



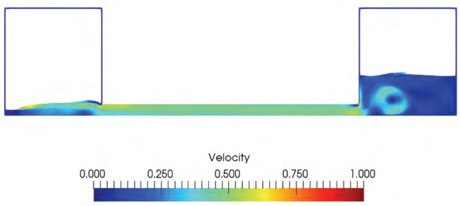
(f) $\omega = 0.62\ rad/sec\ \psi = 90°$



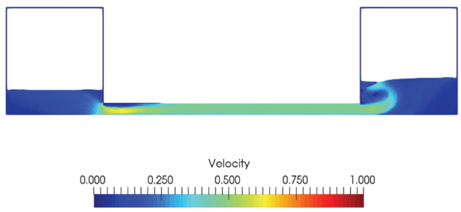
(g) $\omega = 0.44\ rad/sec\ \psi = 135°$



(h) $\omega = 0.62\ rad/sec\ \psi = 135°$



(i) $\omega = 0.44\ rad/sec\ \psi = 180°$



(j) $\omega = 0.62\ rad/sec\ \psi = 180°$

Figure 4: Snapshots of the flow inside the tank at two oscillation frequencies, $\omega = 0.44\ [rad/sec]$ (left column) and $\omega = 0.62\ [rad/sec]$ (right column), respectively. The same phases ψ over the roll period has been compared on each row. Velocity magnitude is show by the colormap.

a roll period of the fluid flow at two frequencies. As expected, it has been shown that gravitational forces have a greater effect on the fluid properties as a slower dynamics is developed, hence at lower frequencies of oscillation.

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